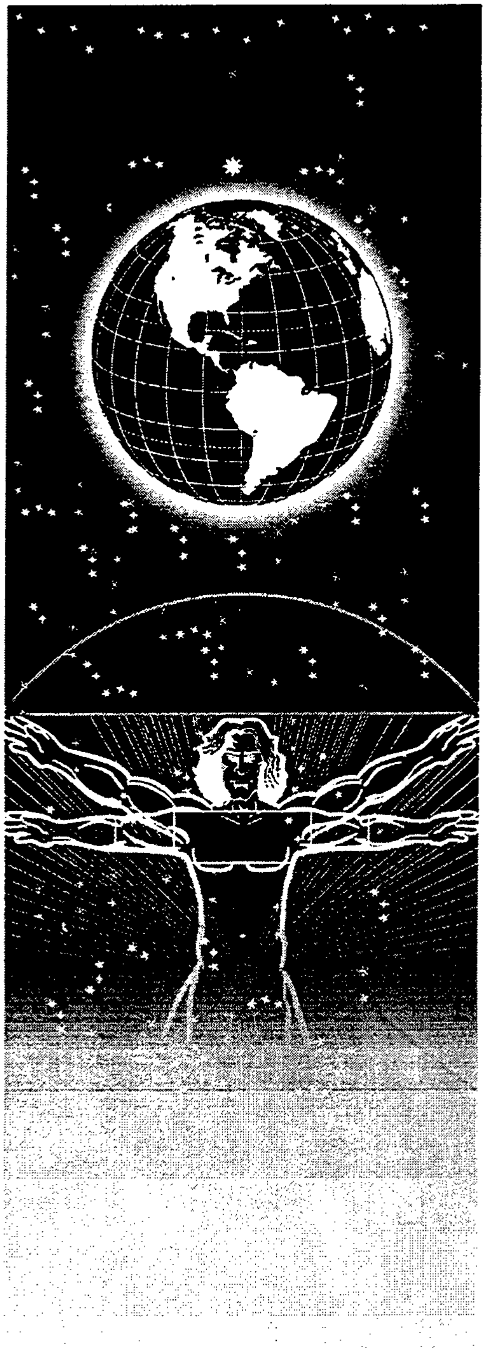
AL/OE-TR-1997-0115



UNITED STATES AIR FORCE
ARMSTRONG LABORATORY

An Evaluation of Structural Damage (Window Breakage) Potential in Caliente, NV Under Current Supersonic Flight Restrictions at Nellis AFB

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January 1997

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AL/OE-TR-1997-0115

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	January 1997	Interim, October 1996 - January 1997

4. TITLE AND SUBTITLE
AN EVALUATION OF STRUCTURAL DAMAGE (WINDOW BREAKAGE) POTENTIAL IN CALIENTE, NV UNDER CURRENT SUPERSONIC FLIGHT RESTRICTIONS AT NELLIS AFB

5. FUNDING NUMBERS
C - F41624-94-C-9007
PE - 65502F
PR - 3005
TA - OB
WU - 41

6. AUTHOR(S)
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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
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Bioenvironmental Engineering Division
Noise Effects Branch
2610 Seventh Street
Wright-Patterson AFB OH 45433-7901

10. SPONSORING/MONITORING
AL/OE-TR-1997-0115

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE
A

13. ABSTRACT *(Maximum 200 words)*
During November 1996 a series of tests was performed in and around Caliente, NV. These tests, performed by the firms of Cambridge Acoustical Associates, Inc., and Wyle Laboratories, Inc., are part of a Small Business Innovative Research (SBIR) project, being sponsored by the Armstrong Laboratory of the United States Air Force. The project objective is to perfect measurement techniques that simulate structural response to sonic booms, and in turn allow one to assess potential damage, especially to unconventional structures. The goals of the Caliente tests were twofold. The first was to provide additional data for the validation of the techniques. The second was to demonstrate the process by which such measurements may be used to perform an evnironmental (structural) damage assessment. This report focuses on the latter.
To limit the overall environmental impact on Caliente, supersonic operations from Nellis AFB have recently been prohibited within five miles of the town. To evaluate the adequacy of this restriction with respect to avoiding structural damage, window damage to be exact, a part of our test plan was devoted to a measurement survey of various windows throughout the town. From these data we have simulated their peak response (stress) to the sonic boom environment evaluated under the above mentioned flight restriction.
Twenty windows were tested, including those of a number of commercial buildings, the library, train station, and one of the auxiliary hospital buildings. (Window installations with a noticeable rattle are not readily simulated and were excluded from the ensemble.) Based on our simulations (Table 3), the least susceptible to damage is a window of the Bureau of Land Management (BLM) Building and a train station window is the most vulnerable. For all windows, no additional breakage is anticipated under current flight restrictions.

14. SUBJECT TERMS
Sonic Boom, Structural Damage, Structural-Acoustic Simulation, Reciprosity

15. NUMBER OF PAGES
20

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UNLIMITED

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I. INTRODUCTION AND SUMMARY

During November 1996 a series of tests was performed in and around Caliente, NV. These tests, performed by the firms of Cambridge Acoustical Associates, Inc. and Wyle Laboratories, Inc., are part of a Small Business Innovative Research (SBIR) project, being sponsored by the Armstrong Laboratory of the United States Air Force. The project objective is to perfect measurement techniques that simulate structural response to sonic booms, and in turn allow one to assess potential damage, especially to unconventional structures. The goals of the Caliente tests were twofold. The first was to provide additional data for the validation of the techniques. The second was to demonstrate the process by which such measurements may be used to perform an environmental (structural) damage assessment. This report focuses on the latter.

To limit the overall environmental impact on Caliente, supersonic operations from Nellis AFB have recently been prohibited within five miles of the town. To evaluate the adequacy of this restriction with respect to avoiding structural damage, window damage to be exact, a part of our test plan was devoted to a measurement survey of various windows throughout the town. From these data we have simulated their peak response (stress) to the sonic boom environment evaluated under the above mentioned flight restriction.

Twenty windows were tested, including those of a number of commercial buildings, the library, train station, and one of the auxiliary hospital buildings. (Window installations with a noticeable rattle are not readily simulated and were excluded from the ensemble.) Based on our simulations (Table 3), the least susceptible to damage is a window of the Bureau of Land Management (BLM) Building and a train station window is the most vulnerable. For all windows tested, no breakage is anticipated under current flight restrictions.

On the other hand, if our damage assessment methodology were applied without accounting for the current flight prohibition, we would predict some damage to be likely. We conclude that the current policy at Nellis AFB, of prohibiting supersonic operations within five miles of Caliente, is necessary and adequate for averting window damage in the town. Should window damage occur, it will likely be in connection with infractions of this policy.

II. THE STRUCTURAL-ACOUSTIC SIMULATION CONCEPT

Our simulation concept uses stationary structural-acoustic tests to characterize how a given structural component, window, wall etc., responds to acoustic noise, to simulate its response to any supersonic operation. (Early validation tests are described in References 1. and 2.) The basic problem is posed in the cartoon of Fig. 1. A supersonic flight produces a sonic boom that impinges upon a structure. It vibrates in response, potentially with levels sufficiently high to cause damage. The boom signature may, but need not, be in the classic N-wave form shown. In the horizontal plane, the orientation of the incident acoustic wave is determined by the flight path. In a vertical plane the elevation angle is determined, as shown, by the local Mach number M=U/c, defined as the ratio of the effective flight speed to the local speed of sound. Our simulation tests are sketched in Figs. 2a and b.

The first step is to identify the vulnerabilities of the structure, window glass breakage, cracks in plaster walls, etc. Second, with our "direct" simulation (Fig. 2a), we measure the vibrations of the vulnerable components, so identified, in response to a stationary acoustic noise source. (The noise from blank shells fired from a small yachting cannon was used for this purpose during our Caliente tests.) The orientation of this acoustic source is determined by the flight path and Mach number of the flight to be simulated. Its stand-off distance is typically 25 to 50 ft. Accelerometers, optical

displacement sensors, and strain gages monitor the vibrations at the critical locations and the data are then analyzed as follows.

The measured response is broken down frequency by frequency, creating a "transfer function" curve. This curve describes the susceptibility of a component to noise induced vibration for a range of frequencies that are typically around 5 to 100 Hz. This curve is then used to compute the response of the component to a specified supersonic operation, either hypothetical or actual. For a hypothetical operation the boom signature may be computed using various computer codes.[3,4] Finally, this "simulated" response is compared to appropriate damage criteria, that is maximum allowable levels, as stated in available published literature.[5]

Alternatively, with our "reciprocal" simulations (Fig. 2b) the fundamental concept remains the same. However, here the transfer function is obtained from measurements of the sound radiated by the structural component when set into vibration by a calibrated mechanical source. (During our Caliente tests, an instrumented hammer provided this mechanical source.) The radiated pressure is measured with a microphone. As with the acoustic source for our direct simulation, the microphone is located a distance about 25-50 ft. from the structure along a line determined by the flight path and Mach number of the flight to be simulated. (The applicability of this test configuration to an incident sonic boom is hardly intuitive. However, it is based on well established structural-acoustic principles and used extensively in practice)

III. CALIENTE SITE SIMULATION MEASUREMENTS

In order to evaluate the potential for breakage under current Nellis AFB flight rules, reciprocal simulation tests were performed on windows of various buildings throughout the town. Reciprocal rather than direct tests were chosen for this purpose because they are quicker to perform and less intrusive. However in some cases, direct tests were being performed for other purposes and these measurements were used to

supplement the data base. Windows with obvious rattling problems were excluded from the study. Their response tends to be "nonlinear", and not readily simulated by any means.

A total of twenty windows were tested, including a number of commercial buildings, the library, train station, and one of the auxiliary hospital buildings. We concentrated on flight paths that produce sonic booms normally incident on the structures of interest, typically one of the more critical cases. Consequently, with our simulations the radiated pressure was monitored in front of the windows. Also, since our primary interest was operations with modest Mach numbers (see Section IV), simulations were carried out with the microphone placed roughly at the same elevation as the window center. Photos of two sites are shown in Fig. 3.

From these data we can simulate the peak acceleration, velocity, or displacement, induced by any specified supersonic operation. For compatibility with available damage criteria, we focused on peak velocity (v_{pk}), which is more readily related to peak stress (σ_{pk}). Specifically, for representative glass parameters (Young's elastic modulus $=10^7$ psi and weight density $=0.82$ lb_f/in^3)

$$\sigma_{pk}(psi) = 82.[1 + .25(a/b)^2]/[1 + (a/b)^2]v_{pk}(in/s) \tag{1}$$

where stress is in units of pounds per square inch, velocity in inches per second, and a/b is the ratio of the smaller to larger lateral lengths of the pane.[6] (Sample comparisons between stresses from sonic booms and simulated values are presented in References 1 and 2, in connection with tests in the vicinity of Edwards AFB, CA. With the only such comparison available from our tests in Caliente, a hospital trailer window, we measured a stress of 233 psi in response to a supersonic flyover versus a simulated value of 229 psi. It should be noted however, that this precision is extraordinary, more typical is an accuracy of 10-20%.)

IV. THE SONIC BOOM ENVIRONMENT

To perform an impact evaluation, the sonic boom environment must be specified. For this study, we assume that the sonic boom signatures are all of the classic N-wave form. This assumption is conservative. Modifications to this shape tend to shift the frequency spectrum to higher frequencies, while structural damage tends to be associated with the lower frequencies. N-shaped sonic booms are fully defined by their duration and peak pressure. We consider durations ranging from 0.1 to 0.2 msec., which covers most of the flights affecting the town. It remains to define the expected peak pressure. Two separate approaches are used, one analytical the other empirical.

A. Analytical Estimate

Using the sonic boom signature prediction code PCBOOM,[3] the peak sonic boom pressure and duration for a variety of aircraft, flight altitudes, and climb and descent profiles, have been calculated at a stand off distance of five miles, laterally or forward. Results are presented in Table 1 for the F-15 aircraft which, on average, is responsible for more of the booms than any other aircraft. Also, being relatively heavy, it tends to produce relatively higher levels. The predicted levels in Table 1 assume steady flight and a standard atmosphere. Under these conditions the maximum computed peak overpressure is 4.3 psf, for a flight altitude of 16,000 ft and a 1.1 Mach No.

B. Empirical Estimate

An extensive sonic boom monitoring program was carried out in 1992, primarily within the Elgin Military Operating Area (MOA).[7] The Elgin MOA is a subsection of the Nellis Range Complex, located south of the Caliente MOA. Supersonic flight tracks from 385 Air Combat Maneuver Instrumentation (ACMI) tapes are presented in Fig. 4.[8] These tapes are a record of roughly one-third of the missions flown during the training period. During these missions, the majority of the sorties were with F-15 and F-16 aircraft. We note that 1992 predates current Caliente supersonic flight restrictions.

Under the current restrictions, we estimate the peak sonic boom pressure to be expected in Caliente from all Nellis AFB operations as follows.

The five-mile outer envelope for the recorded supersonic flights, that is the locus of points at least five miles from all recorded tracks, was determined. This is shown as the dashed line in Fig. 4. Sonic boom monitoring sites were scattered throughout the area. Indicated in the figure are those that were located near the envelope, specifically within two miles, inside or outside. The average and maximum peak overpressures recorded at these three sites for the duration of the study are shown in Table 2. The maximum peak recorded is 2.03 psf (at site No. 24). The corresponding maximum peak-overpressure recorded at the Caliente site (No. 37) from these activities (over a period of 171 days) was 2.34 psf. These values are roughly one half the maximum value predicted above for our hypothetical ensemble of supersonic operations which, conservatively, is used below for our assessment. For perspective, the maximum peak overpressure recorded at any site during the 1992 monitoring effort was 19.35 psf. This may be viewed as an estimate of the sonic boom environment within any MOA, including the Caliente MOA, but in the absence of a flight prohibition.

In summary, we will define the sonic boom environment to be N-shaped pulses with durations ranging from 0.1-0.2 msec., typical of F-15 aircraft. Further, based on our analysis in Section A, we will conservatively assume a peak overpressure of 4.3 psf, a value roughly twice that predicted from Elgin MOA data.

V. DAMAGE CRITERION: MAXIMUM ALLOWABLE LEVELS

A summary of the data base regarding the strength of common construction materials may be found in Ref. 5. For consistency with a linear analysis such as ours, we use a value of 12,800 psi for the mean strength of uncracked, used glass under short term, sonic boom-like, loadings. (This value is based on data as analyzed in Ref. 9, but including the correction factor suggested in Ref. 5.) Any grouping of windows, in

practice, will exhibit variations in strength around these mean values. Statistics for these variations have been compiled for an ensemble of glass panels. Requiring a 95% confidence level that the strength of any of the windows tested will exceed our standard, we arrive at a maximum allowable value that is reduced by twice the standard deviation computed for the ensemble. This reduced strength value gives a damage criterion of 4,736 psi, or 37% of the mean strength. In other words, 5% of glass panes can be expected to fail when initially subjected to an event that produces a stress of 4,736 psi, due to regular variations in glass quality. For any grouping of windows that has passed such a test, however, no further breakage should be expected with subsequent events.

VI. SIMULATED PEAK WINDOW STRESS: DAMAGE ASSESSMENT

Results of our simulations are tabulated in Table 3. Columns 2-4 identify the window. The simulation technique, direct (d) or reciprocal (r) is listed in column 5. In the sixth column we have tabulated the simulated peak window stress for the estimated maximum peak sonic boom overpressure (4.3 psf). These values were predicted by our measurements, using Eq. 1. Lastly, we show our damage assessment in terms of a factor of safety. This factor is defined, for each pane, as the ratio of the maximum allowable stress for used glass (4,736 psi), to the predicted peak stress.

Relative factors of safety yield the relative vulnerabilities of the windows tested. Least susceptible to damage is a window of the Bureau of Land Management (BLM) building and a train station window is the most vulnerable. Absolute levels may be interpreted as follows. For any window with a factor of safety greater than one, there is less than a 5% chance that it would have broken if, as assumed, it were subjected to the hypothesized flight operations (and even less likely for the operations flown during the Elgin Study). Having survived such flights, no further damage is anticipated with future, like operations. This is the case for all of the twenty windows.

If our damage assessment methodology were applied without accounting for the current flight prohibition, we would predict window damage to be considerably more likely. This is readily seen by observing that the maximum peak overpressure recorded anywhere within the Elgin MOA during the study described in Ref. 7 was 19.35 psf, or roughly 4.4 times that used in this assessment. To account, the computed factors of safety in Table 3 would have to be divided by 4.4, resulting in 25% of the 20 sites now having a factor of safety less than 1.0.

Finally, it is informative to compare these site specific damage assessments with the corresponding analysis in Section 4.1.3.3 of the "Environmental Assessment For Supersonic Flight Over The Nellis Range Complex".[10] Specifically, consider the two statements from that document, "The average boom of 1 psf has very little chance of damage...", and "Laboratory studies have shown that properly installed glass in good condition does not break at pressures less than 10 psf". Our results are in full agreement with one exception. The factor of safety for one of the windows, computed for a peak overpressure of 4.3 psf, is not sufficient to accommodate a level of 10 psf. That is, the factor of safety for this window (No. 16) under a 10 psf sonic boom would be (4.3/10) 1.8=0.78, or less than unity.

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4 - Kenneth J. Plotkin, "PCBoom3 Sonic Boom Prediction Model-Version 1.0", Wyle Research Report WR 95-22 (May 1995).

5 - Louis C. Sutherland, Ron Brown and Dawn Goerner, "Evaluation of Potential Damage to Unconventional Structures by Sonic Booms", Wyle Research Report WR 89-14, prepared for Dept. of the Air Force, (OL-AC HSD/YA-NSBIT)(January 1990).

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8 - Personal communication, Kenneth Plotkin, Wyle Laboratories, Inc. (7 January 1997).

9 - R. L. Hershey and T. H. Higgins, Statistical Model of Sonic Boom Structural Damage, FAA-RD 76-87 (July 1976).

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Table 1 - Predicted Sonic Boom peak Overpressure and Duration for F-15E Aircraft Under Steady Flight Conditions

Altitude (kft above MSL)	Peak (psf)/Duration (sec) Mach Number				
	1.1	1.2	1.3	1.4	1.5
Five Mile Lateral Offset					
10	--	--	1.0/.11	0.9/.10	0.9/.10
12	--	0.9/.12	0.8/.11	2.7/.10	2.8/.10
16	--	2.6/.13	2.6/.12	2.6/.11	2.7/.11
20	--	2.3/.14	2.3/.12	2.4/.12	2.5/.11
25	--	2.0/.15	2.1/.13	2.1/.13	2.2/.12
30	--	1.9/.16	1.9/.15	1.9/.14	1.9/.13
Five Mile Forward Standoff					
10	--	--	--	--	--
12	--	--	--	--	--
16	4.3/.13	--	--	--	--
20	3.3/.15	3.6/.12	--	--	--
25	2.8/.16	2.8/.14	3.0/.13	3.1/.12	--
30	--	2.3/.15	2.4/.14	2.5/.13	2.6/.13

Table 2 - Elgin Range Overpressure for Individual Sites Within ±2 miles of Five Mile Track Envelope

Site Number	Operating Days	Total Number of Booms	Overpressure, psf	
			Average	Maximum
24	191	42	0.64	2.03
35	124	13	0.44	0.80
36	90	3	0.41	0.69

Table 3 - Window Damage Potential Under Current Flight Restrictions: Structural Acoustic Simulations

Window Number	Description	Size		Simulation Technique	Simulated Peak Stress[1] (psi)	Factor of Safety[2]
		Width (ft.)	Height (ft.)			
1	Drug Store	8.92	6.92	r	593	8.0
2	Gottfredsons Furniture	5.33	7.00	r	863	5.5
3	Gottfredsons Storage Bldg.	2.67	4.42	r	261	18.2
4	Tru-Value Hardware	3.83	5.75	r	577	8.2
5	BLM Bldg: Center	4.17	3.67	r	383	12.4
6	BLM Bldg: Side	2.67	3.67	r	211	22.5
7	Dolan & Edwards Ins.	6.25	4.75	r	601	7.9
8	That Little Shop in Caliente	5.92	6.00	r	529	8.9
9	Library: SW1	3.67	4.00	d	371	12.8
10	Library: SW2	3.67	4.00	d	375	12.6
11	Library : SW3	3.67	4.00	d	339	14.0
12	Library : SW4	3.67	4.00	d	485	9.8
13	Library: NW1	3.67	4.00	r	934	5.1
14	Library: NW2	3.67	4.00	r	603	7.8
15	RR Station: NW1	2.50	5.00	r	1,505	3.1
16	RR Station: NW2	2.50	5.00	r	2,638	1.8
17	Hospital Admin. Bldg.: Optometrist's Office	2.00	2.42	r	1,069	4.4
18	Hospital Admin. Bldg.: Side Door	2.17	2.33	r	1,176	4.0
19	Hospital: Trailer	2.50	2.17	d	1,646	2.9
20	Hot Springs Hotel	1.25	2.67	r	1,019	4.6

1 Based on a peak sonic boom overpressure of 4.3 psi.

2 Based on a damage stress criterion of 4,736 psi.

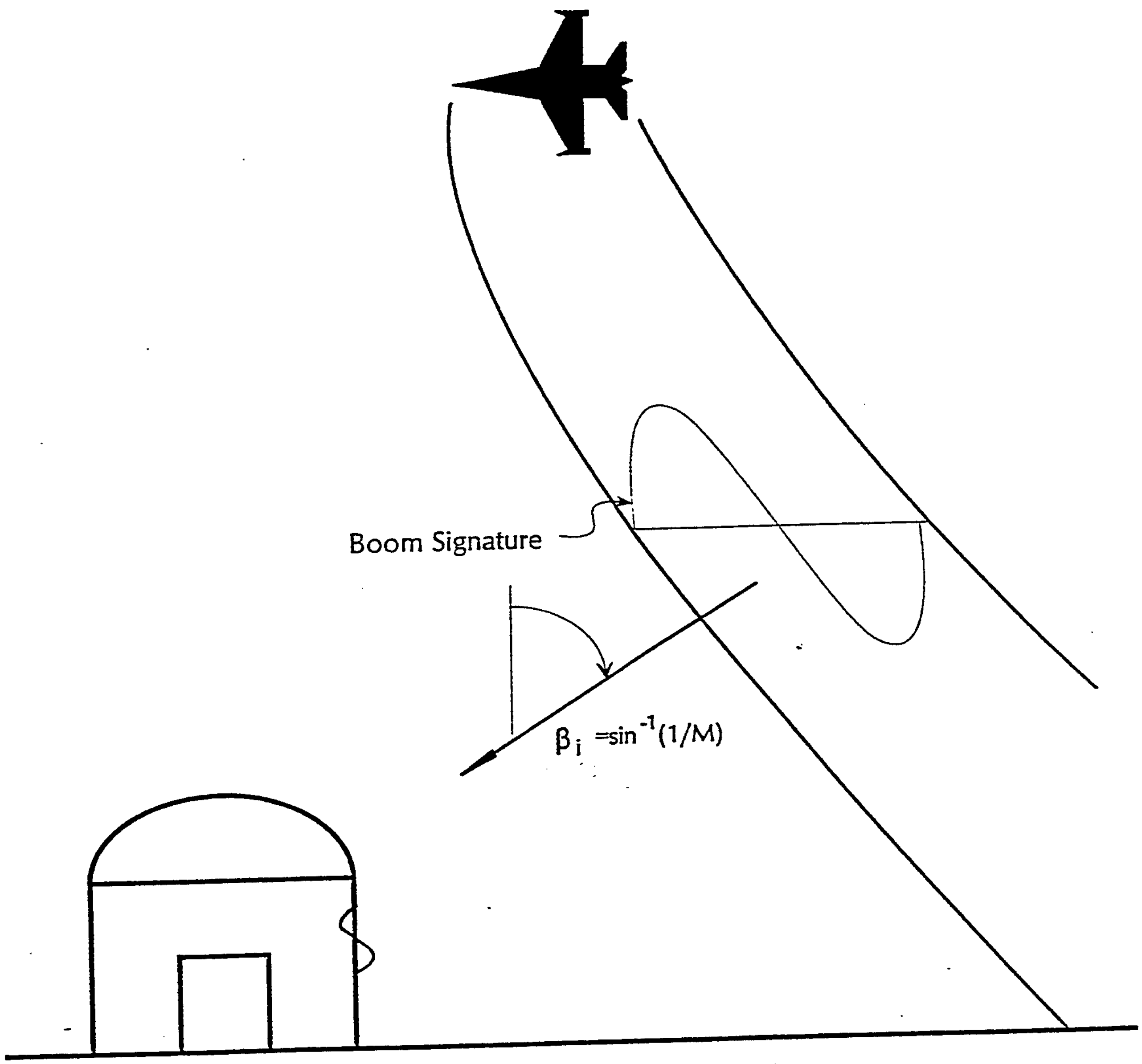


Fig 1. Boom From Supersonic Flyover Vibrates Structure, Potentially Causing Damage (Glass Breakage, Plaster Cracking, Etc.)

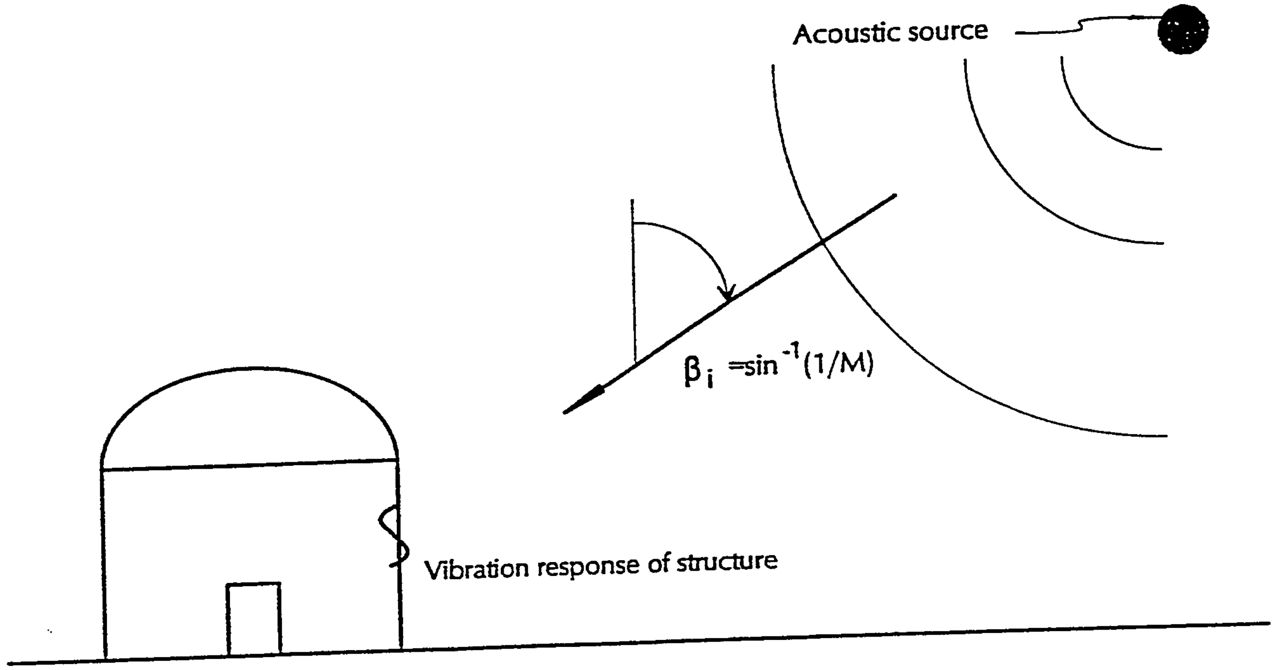


Fig 2a. Direct Structural-Acoustic Simulation of Sonic Boom Impulse Response Function

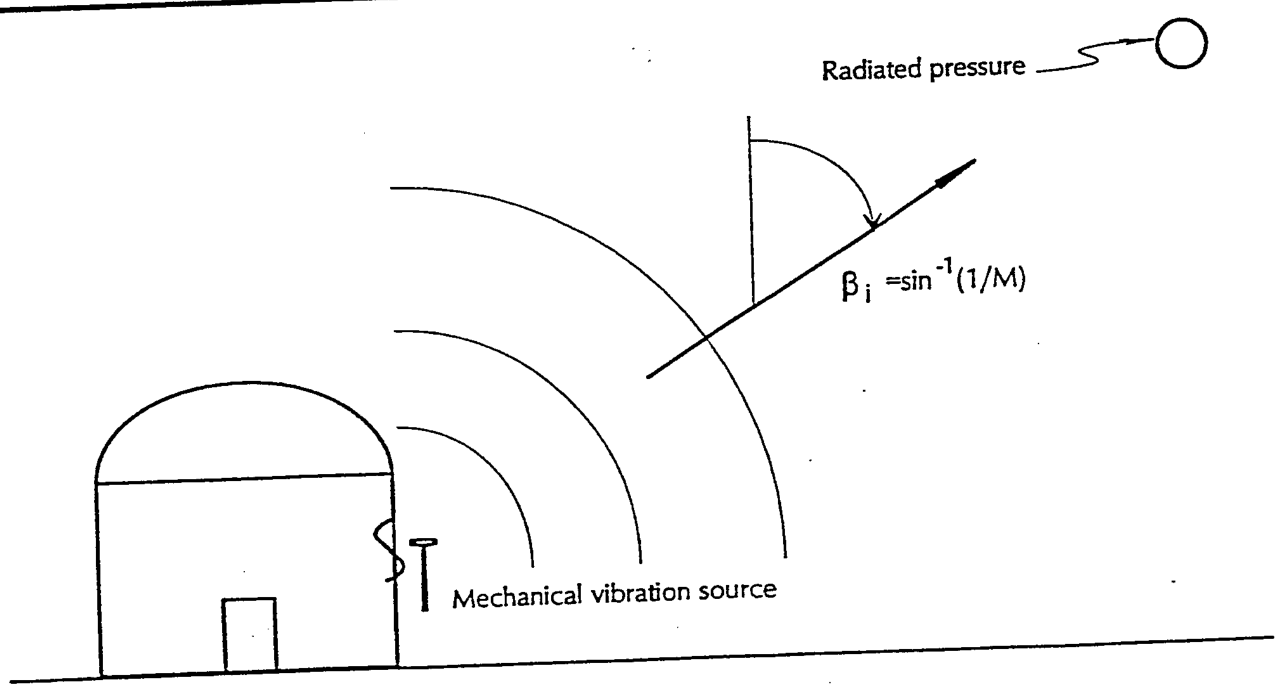
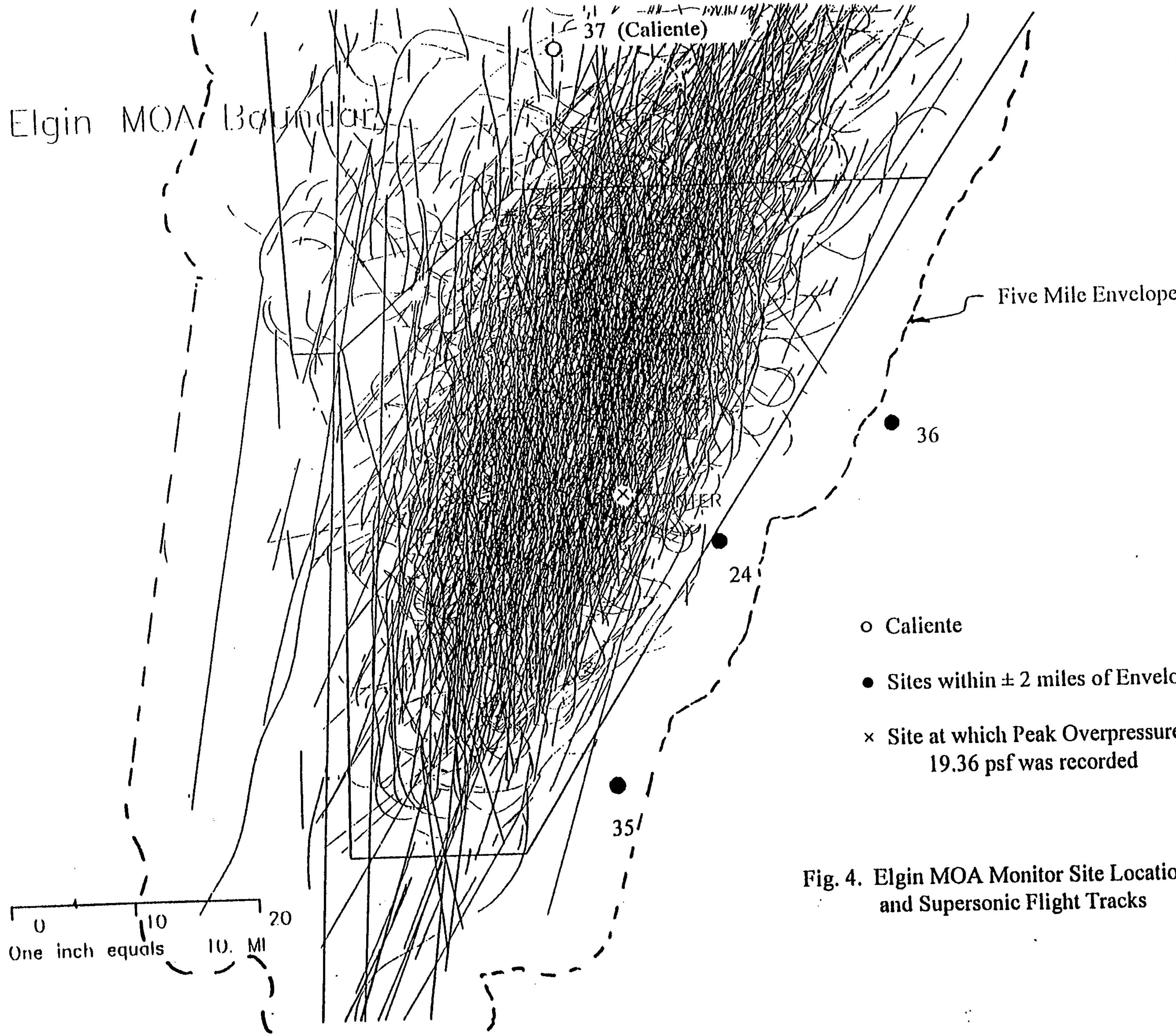


Fig 2b. Reciprocal Structural-Acoustic Simulation of Sonic Boom Impulse Response Function

(a)

(b)

Fig. 3. Microphone Setup for (Reciprocal) Sonic Boom Simulation Tests: (a) Train Station, and (b) Gottfredsons.



o Caliente

● Sites within ± 2 miles of Envelope

× Site at which Peak Overpressure of 19.36 psf was recorded

Fig. 4. Elgin MOA Monitor Site Locations and Supersonic Flight Tracks